

PV Manufacturing R&D Accomplishments and Status

D. Mooney, R. Mitchell, and E. Witt
National Renewable Energy Laboratory

R. King
U.S. Department of Energy

D. Ruby
Sandia National Laboratories

*Presented at the National Center for Photovoltaics and
Solar Program Review Meeting
Denver, Colorado
March 24-26, 2003*



NREL

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

NOTICE

The submitted manuscript has been offered by an employee of the Midwest Research Institute (MRI), a contractor of the US Government under Contract No. DE-AC36-99GO10337. Accordingly, the US Government and MRI retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at <http://www.osti.gov/bridge>

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: <http://www.ntis.gov/ordering.htm>



Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

PV Manufacturing R&D Accomplishments and Status

^w

D. Mooney,¹ R. Mitchell,¹ E. Witt,¹ R. King,² and D. Ruby³

¹National Renewable Energy Laboratory, Golden, CO; ²U.S. Department of Energy, Washington, DC;

³Sandia National Laboratories, Albuquerque, NM

ABSTRACT

The U.S. Department of Energy (DOE) PV Manufacturing Research and Development Project has worked for 11 years in partnership with the U.S. photovoltaic industry to reduce manufacturing costs while significantly scaling up production capacity. Over this period, the PV Manufacturing R&D Project has issued seven solicitations for partnerships that have resulted in over 50 cost-shared R&D subcontracts that addressed the cost and capacity goals of the Project, including 10 that are currently active. The previous and current contracts have typically focused on addressing Project goals in one of two areas: module manufacturing and balance-of-systems (BOS)/systems work. The majority of the DOE investment has been targeted toward module manufacturing. The partnerships have resulted in a significant and measurable increase in PV module/systems production capacity, a decrease in PV manufacturing costs, and a subsequent return on the joint public and private investments facilitated by the Project.

1. Introduction

In 1990, DOE, working with the National Renewable Energy Laboratory and Sandia National Laboratories, initiated the Photovoltaic Manufacturing Technology (PVMaT) Project in partnership with the U.S. photovoltaic industry to accelerate PV production scale-up and cost reduction. Since the inception of PVMaT (now referred to as the PV Manufacturing R&D Project), the U.S. DOE and industry have together invested over \$140M (\$80M U.S. DOE share/\$60M industry share) toward the goals of the Project. This has been accomplished through six procurements, including the latest and currently active procurement titled “In-line Diagnostics and Intelligent Processing (IDIP).” The details of these procurements have been described in a number of other papers [1-16] and will not be reviewed here. Generally, over the course of these procurements, subcontracts have focused on three main areas. The first, and the area that has received the majority of PV Manufacturing R&D money, is process-specific improvements for individual companies’ module manufacturing products and processes. Subcontracts have also been awarded to address generic issues so that the R&D results of these efforts might be applicable to, and adopted by, a number of members of the U.S. PV industry. The third main area is related to BOS and systems integration manufacturing improvements and scale-up. The subcontracted R&D funded in the first five procurements has all been completed. The research under the IDIP solicitation is under way and will be summarized in the following section.

2. Status

The IDIP Request for Letters of Interest (LOI) was structured to solicit responses in the areas of research and development for PV System and Component Technology and Module Manufacturing Technology. The IDIP Request for LOIs received 22 responses. Of these, six responded to the System and Component category and 16 responded to the Module Manufacturing category. Table 1 lists the responders that were determined to be in the competitive range and with whom subcontracts have been entered into to this point. Negotiations are ongoing with an additional four companies not listed in Table 1, but who were in the competitive range of the IDIP solicitation.

Table 1. IDIP Subcontractors

Subcontractor	Subcontract Title
<i>PV System and Component Category</i>	
PowerLight Corporation	PowerGuard Lean Manufacturing
Schott Applied Power	Plug and Play Components for Building Integrated PV Systems
Specialized Technology Resources	Development of New Low-Cost, High-Performance PV Module Encapsulant/Packaging Materials
Xantrex	PV Inverter Products Manufacturing and Design Improvement for Cost Reductions and Performance Enhancement
<i>Module Manufacturing Category</i>	
BP Solar	Large Scale PV Module Manufacturing Using Ultrathin Polycrystalline Silicon Solar Cells
Energy Photovoltaics, Inc.	Productivity Enhancement for Manufacturing of Amorphous Silicon PV Modules
Evergreen Solar	Innovative Approaches to Low Cost Module Manufacturing of String Ribbon Si PV Modules
ITN Energy	Trajectory Oriented and Fault Tolerant Based, Intelligent Process Control for Flexible CIGS PV Module Manufacturing
RWE Schott Solar	EFG Technology and Diagnostics R&D for Large-Scale PV Manufacturing
Shell Solar Industries	PV Manufacturing R&D – Integrated CIS Thin-film Manufacturing Infrastructure
Sinton Consulting	Development of an In-Line Minority-Carrier Lifetime Monitoring Tool for Process Control During Fabrication for Crystalline Silicon Solar Cells

3. Progress Toward PV Manufacturing R&D Goals

To measure and track the progress of the PV Manufacturing R&D Project's impact on module cost and production capacity, direct module manufacturing costs and manufacturing capacity have been collected in collaboration with the Project's module manufacturing partners. In addition to supplying the most recent year's data, module manufacturing partners also supply their projections for the coming five years. Figure 1 shows the 2002 data of 15 PV Manufacturing R&D module manufacturing partners who had active manufacturing lines in 2002. (A partners in this context refers to a subcontractor with a specific technology. Within the 15 partners, there are 11 companies represented.) Figure 1 shows continued progress toward meeting the Project goals of decreasing direct manufacturing costs and increasing production capacity.

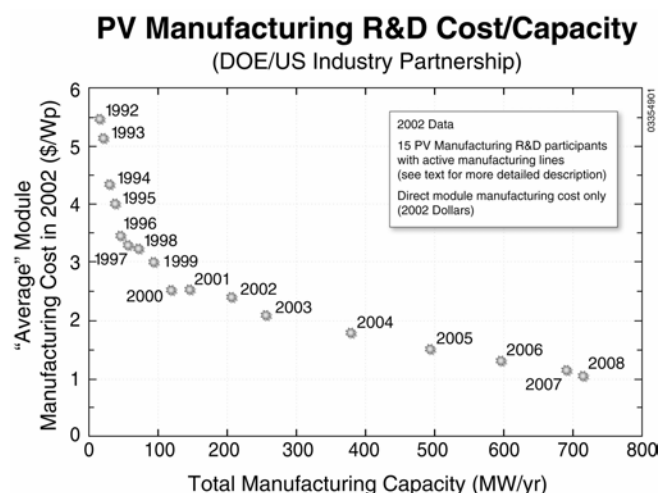


Fig. 1 PV Manufacturing R&D participants cost and capacity data.

The PV module manufacturing cost shown on the vertical axis of Figure 1 represents the weighted average of the 15 manufacturers' direct module manufacturing costs in 2002 dollars. Each manufacturer's cost was weighted in the average based on their contribution to the total manufacturing capacity. The direct costs that are included relate only to those costs directly associated with module production and do not include such costs as research, marketing/sales, or general and administrative expenses. The production capacity that is shown on the horizontal axis is the total capacity of the 15 manufacturers and does not represent the actual module production of the partners, but illustrates the *potential* production if all the plants were running at full capacity. Costs that are shown are also expected to scale with the production level, and therefore, direct costs shown are only those that are commensurate with full production.

Looking at the data through 2002, it is seen that total module production capacity has grown from 13 MW at the start of PVMaT subcontracts in 1992 to 205 MW in 2002 – a 16-fold increase or a 32% average annual growth in production capacity among these PV Manufacturing R&D

participants. During the same period, direct module manufacturing costs in 2002 dollars have dropped from \$5.47/Wp in 1992 to \$2.42/Wp. This represents a total price reduction of about 56%, or an average *annual* drop in direct module manufacturing cost of about eight percent. In terms of technology learning curves, these data reflect an average 18% drop in direct manufacturing costs for each doubling of production capacity.

When compared to a similar graph using 2001 data [16], it should be noted that there is shift downward in production capacity and a shift upward in direct module manufacturing costs. These shifts are the result of the closure of two manufacturing plants during 2002, coupled with more conservative projections on the part of a number of manufacturers when projecting future capacity and costs. It should also be noted that the data through 2002 include 15 partners, whereas the data from 2003 to 2008 include projections without the two factories that closed.

Figure 2 shows the ratio of non-thin-film production capacity to thin-film production capacity. When compared to a previous similar graph [16], a difference can be seen in the out-year projections. A portion of this shift is related to the closure of the two plants in 2002 referenced above. The significant increase in the ratio that reflected planned thin-film capacity increases has moderated, and the ratios for projections through 2008 show a slightly more level trend.

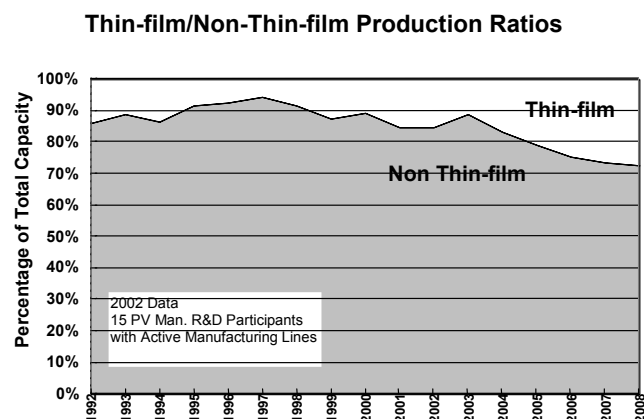


Fig. 2 Ratios of thin-film to non-thin-film production levels shown as percentage of total production.

4. Recapture of Research Funding

Along with cost and capacity data, PV Manufacturing R&D module manufacturing partners have also provided the Project with manufacturing cost reductions that can be directly attributed to the efforts completed under their cost-shared subcontracts. In addition to the raw cost-savings data, manufacturers have also provided information related to how those cost reductions will be allocated. The recapture of the money invested by both the U.S. DOE and the companies themselves can be determined by analyzing how much of the cost reductions will be passed on to consumers through lower prices and how much will be retained by the company as increased profits, debt reduction, or capital investment. Figures 3 and 4 show the breakeven points for both the public and participating

companies. The breakeven point is defined as the point at which the cumulative manufacturing cost savings equals the total amount invested (in 2002 dollars). The industry recovery as shown in Figure 4 reflects the total investment and recapture of R&D funding in 2002 dollars for all participating module manufacturers and is not a reflection of the investment recapture for an individual company. As can be seen in Figure 3, accounting for the investment through the end of calendar year 2002, the benefit to the public through cumulative lower pricing exceeded the U.S. DOE (public) investment in 1999. As of the end of 2002, the simple return on the public's investment stands at 366% since the project's inception.

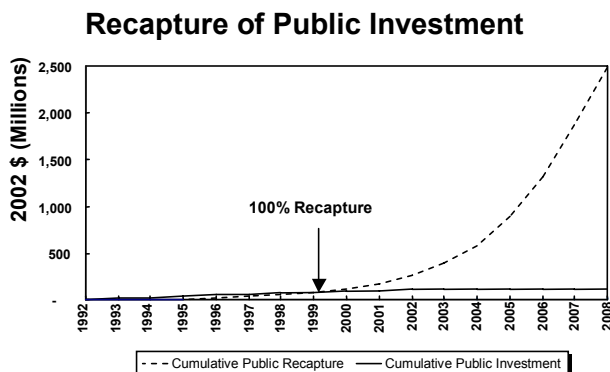


Fig. 3 Recapture of the public's investment in the PV Manufacturing R&D Project.

Figure 4 illustrates that the industry reached a breakeven for their investment in 1998. As of the end of 2002, the simply return on the industry's investment stands at 319 percent. In addition to breakeven points for both the public and private sectors, Figures 3 and 4 also depict, based on projections of the participating module manufactures, that the cumulative benefits will continue to accrue well into the future.

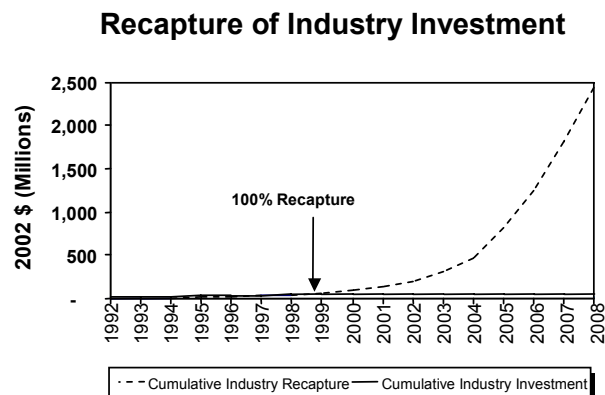


Fig. 4 Recapture of industry's investment in PV Manufacturing R&D improvements.

5. Conclusions

Work on subcontracted R&D under the IDIP solicitation of the PV Manufacturing R&D Project is currently under way. Interest on the part of the U.S. PV industry has remained very strong throughout the Project, with 22 LOIs received for the latest solicitation. The Project has continued to address its goals of reducing direct manufacturing costs and increasing production capacity. Average direct manufacturing costs (in 2002 dollars) have been reduced 56% since the first subcontracts were issued in 1992, while production capacity has increased 16-fold, assisting the industry in meeting the demands of a rapidly growing market. Projections from the Project's partners show this trend continuing, with projections through 2008 for further direct manufacturing cost reductions to \$1.07 per peak watt accompanied by an increase in production capacity to over 700 MW. As work on the IDIP procurement continues, investigation is under way to determine future activities that will support research in product quality and facilitate the further acceleration of the Project's cost reduction and increased capacity goals.

6. References

- [1] C.E. Witt, L.O. Herwig, R. Mitchell, and G.D. Mooney, "Status of the Photovoltaic Manufacturing Technology (PVMaT) Project," *Proceedings of the 22nd IEEE Photovoltaics Specialists Conference*, Las Vegas, Nevada, October 1991.
- [2] C.E. Witt, R.L. Mitchell, G.D. Money, L.O. Herwig, D. Hasti, and R. Sellers, "Progress in Phases 2 and 3 of the Photovoltaic Manufacturing Technology Project (PVMaT)," *Proceedings of the 23rd IEEE Photovoltaics Specialists Conference*, Louisville, Kentucky, May 1993.
- [3] C.E. Witt, L.O. Herwig, R.L. Mitchell, H.P. Thomas, R. Sellers, and D.S. Ruby, "Recent Progress in the Photovoltaic Manufacturing Technology Project (PVMaT)," *Proceedings of the 1st World Conference on Photovoltaics*, Waikoloa, Hawaii, December 1994.
- [4] R.L. Mitchell, C.E. Witt, H.P. Thomas, L.O. Herwig, D.S. Ruby, and C.C. Aldrich, "Benefits from the U.S. Photovoltaic Manufacturing Technology Project," *Proceedings of the 25th IEEE Photovoltaics Specialists Conference*, Washington, D.C., May 1996.
- [5] R.L. Mitchell, C.E. Witt, and H.P. Thomas, "Photovoltaic Manufacturing Technology (PVMaT) Project - Latest Results," *Proceedings of the NREL/SNL Photovoltaic Program Review Meeting*, Lakewood, Colorado, November 1996.
- [6] R.L. Mitchell, C.E. Witt, H.P. Thomas, L.O. Herwig, D.S. Ruby, Richard King, and C.C. Aldrich, "Progress Update on the U.S. Photovoltaic Manufacturing Technology Project," *Proceedings of the 26th IEEE Photovoltaics Specialists Conference*, Anaheim, CA, October 1996.
- [7] C.E. Witt, R.L. Mitchell, M. Symko-Davies, H.P. Thomas, R. King, and D.S. Ruby, "Current Status and Future Prospects for the PVMaT Project," *Presented at*

- [8] C.E. Witt, R.L. Mitchell, M. Symko-Davies, H.P. Thomas, R. King, and D.S. Ruby, "Ten Years of Manufacturing R&D in PVMaT – Technical Accomplishments, Return on Investment, and Where Do We Go Next," *Proceedings of the 28th IEEE Photovoltaics Specialists Conference*, Anchorage, Alaska, September 2000.
- [9] C.E. Witt, T. Surek, R.L. Mitchell, M. Symko-Davies, and H.P. Thomas, "Terrestrial Photovoltaics Technologies - Recent Progress in Manufacturing R&D," *Presented at the ASME 2000 34th National Heat Transfer Conf.*, Pittsburgh, Pennsylvania, August 2000.
- [10] C.E. Witt, R.L. Mitchell, H.P. Thomas, M.L. Symko, R. King, and D.S. Ruby, "Manufacturing Improvements in the Photovoltaic Manufacturing Technology (PVMaT) Project," *Proceedings of the 2nd World Conference on Photovoltaic Solar Energy Conversion*, Vienna, Austria, July 1998.
- [11] R.L. Mitchell, M.L. Symko, H.P. Thomas, and C.E. Witt, "PVMaT 1998 Overview," *Presented at the NCPV Photovoltaic Program Review Meeting*, Denver, Colorado, September 1998.
- [12] M. Symko-Davies, R.L. Mitchell, C.E. Witt, H.P. Thomas, R. King, and D.S. Ruby, "Decade of PV Industry R&D Advances in Silicon Module Manufacturing," *Proceedings of the 28th IEEE Photovoltaics Specialists Conference*, Anchorage, Alaska, September 2000.
- [13] W. Bower, H.P. Thomas, B. Kroposki, R. Bonn, and T. Hund, "Balance-of-System Improvements for Photovoltaic Applications Resulting from the PVMaT 4A1 Program," *Proceedings of the 26th IEEE Photovoltaics Specialists Conference*, Anaheim, CA, October 1996.
- [14] H.P. Thomas, B. Kroposki, P. McNutt, C.E. Witt, W. Bower, R. Bonn, and T.D. Hund, "Progress in Photovoltaic System and Component Improvements," *Proceedings of the 2nd World Conference on Photovoltaic Solar Energy Conversion*, Vienna, Austria, July 1998.
- [15] H.P. Thomas, B. Kroposki, C.E. Witt, and W. Bower, "Progress in Photovoltaic Components and Systems," *Presented at the 16th European Photovoltaic Solar Energy Conference and Exhibition*, Glasgow, Scotland, U.K., May 2000.
- [16] R.L. Mitchell, C.E. Witt, R. King, and D. Ruby, "PVMaT Advances in the Photovoltaic Industry and the Focus of Future PV Manufacturing R&D," *Presented at the 29th IEEE Photovoltaics Specialist Conference*, New Orleans, Louisiana, 2001.

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE May 2003		3. REPORT TYPE AND DATES COVERED Conference Paper
4. TITLE AND SUBTITLE PV Manufacturing R&D Accomplishments and Status			5. FUNDING NUMBERS PVP3.6101	
6. AUTHOR(S) D. Mooney ¹ , R. Mitchell ¹ , E. Witt ¹ , R. King ² , and D. Ruby ³				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) ¹ National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401-3393 ² U.S. Department of Energy, Washington, DC ³ Sandia National Laboratories, Albuquerque, NM			8. PERFORMING ORGANIZATION REPORT NUMBER NREL/CP-520-33628	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) The U.S. Department of Energy (DOE) PV Manufacturing Research and Development program has worked for 11 years in partnership with the U.S. photovoltaic industry to reduce manufacturing costs while significantly scaling up production capacity. Over this period, the PV Manufacturing R&D Program has issued seven solicitations for partnerships that have resulted in over 50 cost-shared R&D subcontracts that addressed the cost and capacity goals of the Program, including 10 that are currently active. The previous and current contracts have typically focused on addressing Program goals in one of two areas – module manufacturing and balance of systems (BOS)/systems work. The majority of the DOE investment has been targeted toward module manufacturing. The partnerships have resulted in a significant and measurable increase in PV module/systems production capacity, a decrease in PV manufacturing costs, and a subsequent return on the joint public and private investments facilitated by the Program.				
14. SUBJECT TERMS PV Manufacturing R&D; partnership; costs; capacity; recapture; benefits			15. NUMBER OF PAGES	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL	